PASSIVE TELEMETRY SYSTEM FOR IMPLANTABLE MEDICAL DEVICE

Field of the Invention

This invention pertains to implantable medical devices such as cardiac
pacemakers and implantable cardioverter/defibrillators. In particular, the invention
relates to a telemetry system and method for such devices.

Background

Implantable medical devices, including cardiac rhythm management devices such
as pacemakers and implantable cardioverter/defibrillators, typically have the capability to
communicate data with a device called an external programmer via a radio-frequency
telemetry link. One use of such an external programmer is to program the operating
parameters of an implanted medical device. For example, the pacing mode and other
operating characteristics of a pacemaker are typically modified after implantation in this
manner. Modern implantable devices also include the capability for bidirectional
communication so that information can be transmitted to the programmer from the
implanted device. Among the data which may typically be telemetered from an
implantable device are various operating parameters and physiological data, the latter
either collected in real-time or stored from previous monitoring operations.

Telemetry systems for implantable medical devices utilize radio-frequency (RF)
energy to enable bidirectional communication between the implantable device and an
external programmer. An exemplary telemetry system for an external programmer and a
cardiac pacemaker is described in U.S. Patent No. 4,562,841, issued to Brockway et al.
and assigned to Cardiac Pacemakers, Inc., the disclosure of which is incorporated herein
by reference. A radio-frequency carrier is modulated with digital information, typically
by amplitude shift keying where the presence or absence of pulses in the signal constitute
binary symbols or bits. The external programmer transmits and receives the radio signal
with an antenna incorporated into a wand that can be positioned in proximity to the
implanted device. The implantable device also generates and receives radio signals by

means of an antenna, typically formed by a wire coil wrapped around the periphery of the inside of the device casing.

Most conventional radio-frequency telemetry systems used for implantable medical devices such as cardiac pacemakers utilize inductive coupling between the antennas of the implantable device and an external programmer in order to transmit and receive RF signals. Because the induction field produced by a transmitting antenna falls off rapidly with distance, such systems require close proximity between the implantable device and a wand antenna of the external programmer in order to work properly, usually on the order of a few inches. This requirement is an inconvenience for a clinician and limits the situations in which telemetry can take place.

Wireless radio-frequency communication over greater distances requires the use of far-field telemetry. Communication using far-field radiation can take place over much greater distances which makes it more convenient to use an external programmer. Also, the increased communication range makes possible other applications of the telemetry system such as remote monitoring of patients and communication with other types of external devices.

In order for a substantial portion of the energy delivered to an antenna to be emitted as far-field radiation, the wavelength of the driving signal should not be very much larger than the length of the antenna. Far-field radio-frequency communications with an antenna of a size suitable for use in an implantable device therefore requires a carrier in the frequency range of between a few hundred MHz to a few GHz. An active transmitter for this frequency range requires special RF components (typically including SiGe or GaAs semiconductor devices) that consume a significant amount of power (typically tens of milliwatts). There is no problem with providing such a transmitter in an external programmer which is connected to an external power source. Implantable medical devices, however, are powered by a battery contained within the housing of the device that can only supply a limited amount of peak power, and many batteries in use today are not capable of supplying power sufficient to power an RF transmitter. Even if sufficient power can be supplied, the battery has a limited life span. When the battery fails, it must be replaced which necessitates a reimplantation procedure. Implantable

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medical devices are also necessarily small, with only a limited space available for locating complex RF circuitry, especially in view of the fact that the RF circuitry needs to be isolated and shielded from the rest of the device circuitry to prevent interference. These factors make it difficult to satisfactorily implement a far-field RF transmitter in an

5   implantable medical device.

Summary of the Invention

The present invention is a telemetry system and method that enables far-field radio-frequency data transmission from an implantable medical device to an external

10   device without the need for an active transmitter. In accordance with the invention, a radio-frequency carrier signal is transmitted from an antenna of the external device to an antenna of the implantable device. The impedance of the implantable device antenna is adjusted in a time varying manner with a tuning circuit in accordance with digital message data that is to be transmitted. The result is a phase modulated carrier signal

15   reflected from the implantable device antenna back to the external device. The phase modulated carrier signal can then be demodulated at the external device to recover the digital message data.

Brief Description of the Drawings

20   Fig. 1 illustrates the basic components of a passive telemetry system.

Fig. 2 is a diagram of a data transmitter for the implantable device.

Fig. 3 is a block diagram of an external device receiver for binary phase-shift keying.

Fig. 4 is a block diagram of an external device receiver for quadrature phase-shift

25   keying.

Fig. 5A is an exemplary circuit for differential data encoding.

Fig. 5B is a block diagram of an external device receiver for differential binary phase-shift keying.

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Detailed Description

The present invention is a system and method for providing RF telemetry between an implantable medical device and an external device in which data is passively transmitted from the implantable device. The system allows far-field RF telemetry to be

5 implemented without the need for an active transmitter in the implantable device Fig. 1 shows the primary telemetry components of an external device 100 and an implantable medical device 200. In this exemplary embodiment, the external device and the implantable device are microprocessor-based devices having microprocessors 102 and 202, respectively, that serve as controllers for overall device operation as well as

10 supervising telemetry. The implantable device 200 may be a cardiac rhythm management device such as a pacemaker or implantable cardioverter/defibrillator, while the external device is a data-gathering device such as an external programmer or remote monitor.

The microprocessor 102 of the external device is interfaced to a radio-frequency transmitter 110 and receiver 120 that are both connected to an antenna 101. A directional

15 coupler 130 passes radio-frequency signals unidirectionally from the transmitter to the antenna and from the antenna to the receiver. Upon a command from the microprocessor, the transmitter 110 generates a radio-frequency carrier signal for a specified time period that is emitted from the antenna 101. The transmitted carrier signal then reaches the antenna 201 of the implantable device where it is reflected back to the antenna 101 of the

20 external device. By varying the impedance of the antenna 201, the implantable device modulates the phase of the reflected carrier in accordance with digital message data that is to be transmitted to the external device. After reaching the antenna 101, the reflected carrier signal is conveyed through the directional coupler to the receiver 120 where the signal is demodulated to extract the digital message data. The digital data may then be

25 processed and interpreted by software executed by the microprocessor 102.

The directional coupler 130 of the external device enables the receiver 120 to receive signals without interference from signals simultaneously emitted by the antenna 101 that originate from the transmitter 110. As an alternative to the directional coupler, separate antennas with orthogonal linear polarization states can be provided for the

30 transmitter and receiver, with the antenna of the implantable device then designed to

reflect elliptically polarized radio waves. For example, the antennas of the external device transmitter and receiver may be monopole or dipole antennas oriented at right angles to one another, while the implantable device antenna is a loop or helical antenna. The external device receiver antenna is blind to waves radiated by the transmitter antenna

5   but is sensitive to waves reflected by the implantable device antenna, thus enabling simultaneous radiation of the carrier signal by the transmitter antenna and reception of the reflected carrier by the receiver antenna. Another alternative to using a directional coupler is for the external device to transmit the carrier signal in discrete bursts and receive the signal reflected by the implantable device between the bursts, with the

10   transmitter and receiver being alternately connected to the antenna by a switch.

In the implantable device 200, the microprocessor is interfaced to a data transmitter 210 that includes circuitry for encoding digital message data received from the microprocessor and time-varying the impedance of the antenna 201 accordingly. A radio-frequency carrier signal reflected from the antenna while the impedance is so varied is

15   thus phase modulated with the digital data using some variant of phase-shift keying. In one embodiment, the implantable device periodically varies the antenna impedance with the same message data in order to transmit the data whenever an external device transmits a carrier signal. In another embodiment, a radio-frequency receiver 220 is provided as shown in the figure that enables the external device to communicate with the implantable

20   device. Such radio-frequency communications may take place over a different communications channel using a different carrier frequency and/or modulation method than used in the passive telemetry system described herein. When the implantable device receives a data request from the external device, it may then expect the carrier signal to be transmitted and can initiate a data transfer by varying the impedance of the antenna.

25   Although a radio-frequency receiver does consume a significant amount of power, this is minimized by only using it for short periods in order to initiate communications with passive telemetry.

Fig. 2 shows an exemplary implementation of the data transmitter 210 of the implantable device. Digital message data m(t) is passed to a symbol encoder 205 that

30   includes a digital-to-analog converter for encoding the digital data into voltage level

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symbols that are output serially at a specified symbol rate and used to vary the impedance
of the antenna 201 via a tuning circuit. For example, binary symbols are generated by
outputting one voltage level for each 1 in the message data m(t) and another voltage level
for each 0. The tuning circuit is connected to the antenna 201 and thus constitutes part of

5 the impedance presented to a carrier signal reflected by the antenna. In this embodiment,
the tuning circuit is an LC tank circuit with a voltage-controlled capacitance. As shown
in the figure, the tank circuit includes an inductor 210, a capacitor 209, and a varactor
diode 207. The voltage level symbols output by the symbol encoder 205 are applied
across the varactor diode 207 and thereby vary the capacitance of the tank circuit in

10 accordance therewith. Since the phase of a waveform reflected by the antenna depends
upon the complex impedance of the tank circuit, the voltage level symbols are thus
converted to phase angle symbols in the reflected carrier signal. The symbol rate is
normally specified such that the symbol period T_S is some number of cycles of the carrier
signal. Also shown in the figure is a choke inductor 206 for isolating the symbol

15 encoder from radio-frequency signals and a DC blocking capacitor 208 that isolates the
antenna from the voltage applied to the varactor diode.

Fig. 3 shows an exemplary implementation of an external device receiver 120 for
demodulating a radio-frequency carrier reflected from the implantable device. In this
example, the reflected carrier x(t) is modulated with digital message data m(t) by the

20 implantable device using binary phase-shift keying and then synchronously demodulated
at the external device. In conventional binary phase-shift keying, the phase of the carrier
is either shifted 180 degrees or not in accordance with the modulating digital data. In
synchronous demodulation, a reference carrier signal is used to detect the phase of the
received signal. A correlator 125, made up of mixer 121 and integrator 122, correlates

25 the received signal x(t) with a reference carrier signal R(t) over a symbol period T_S in
order to convert the phase angle symbols contained in x(t) into voltage level symbols.
The voltage level symbols are then decoded by symbol decoder 123 to result in the
extracted message data m(t). Fig. 4 shows another example of a receiver 120 in which
the reflected carrier x(t) is modulated with message data using quadrature phase-shift

30 keying where two bits of digital data are represented by one of four phase angle symbols,

normally spaced 90 degrees apart. In this case, the signal x(t) is correlated with a reference signal R(t) over the symbol period T_S by correlator 125a in order to demodulate the in-phase component of the signal x(t). The quadrature component of the signal x(t) is demodulated by correlator 125b which correlates x(t) with the reference signal R(t) shifted by 90 degrees, the latter being generated by phase shifter 127. Symbol decoders 123a and 123b then convert the voltage level symbols output by correlators 125a and 125b, respectively, into binary digital data which are input to multiplexer 124 to generate the extracted message data m(t). Other embodiments may use M-ary phase-shift keying where additional phase angle symbols are used to represent greater numbers of bits. The upper limit on the amount of information that can be packed into a symbol is determined by the signal-to-noise ratio of the communications channel.

In one embodiment, the reference carrier R(t) used in the examples of Figs. 3 and 4 may be a locally generated signal using the same oscillator used to generate the carrier signal emitted by the antenna 101. In that case, the phase of the reference signal R(t) must match the phase of the unmodulated carrier received from the implantable device in order to demodulate the received signal. Since the phase of the received signal x(t) varies with the distance between the implantable device and the external device, the implantable device may, at specified times according to a predetermined communications protocol, reflect radio-frequency carrier signal with alignment or reference symbols having no phase shift with which the external device receiver may synchronize the reference carrier signal.

The external device may transmit the carrier signal to the implantable device in bursts having durations of one symbol period or a plurality of symbol periods. In the former case, the phase shift of each reflected burst is detected in order to determine which symbol is being transmitted. A burst with a reference symbol (i.e., with zero phase shift) is periodically reflected by the implantable device so that the phase of reference carrier can be adjusted, and succeeding bursts are then transmitted at regular intervals in order to maintain the proper phase relationship between the reference carrier and the reflected carrier. In an exemplary implementation, a 403 MHz carrier is employed for data transmission, as the FCC has recently set aside a nominal frequency of 403 MHz

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channelized into 300 kHz channels for medical device communications. In order to constrain the data transmission to a bandwidth of less than 300 kHz, 10 microsecond bursts of the carrier are transmitted, with each burst separated by an interval of 10 microseconds. With one symbol per burst, the symbol rate is then 50 kilosymbols per

5   second, which is well below the theoretical maximum of 600 kilosymbols per second allowed by the 300 kHz channel. If the data is encoded as two bits per symbol (i.e., quadrature phase-shift keying), the maximum data rate attainable by this particular scheme is then 100 kilobits per second, minus the overhead associated with periodically transmitting reference symbols.

10   In another embodiment, each burst of the carrier signal transmitted by the external device is modulated with a plurality of symbols by the reflecting antenna of the implantable device. The duration of the bursts may then be made arbitrarily long so that data transmission is continuous while the external device is transmitting. Each reflected burst may then contain one or more reference symbols in order to maintain the locally

15   generated reference carrier at the proper phase. As an alternative to employing a reference carrier to demodulate the reflected signal, the data may be transmitted by the implantable device using differential phase-shift keying. In this type of modulation, symbols are encoded into the carrier waveform as the phase shifts between succeeding symbol periods rather than with respect to a reference carrier. This allows demodulation

20   to be accomplished without the need for generating a reference carrier. Fig. 5A shows an example circuit by which the implantable device may differentially encode digital message data m(t) received from the microprocessor 202. The data signal m(t) is fed to one of the inputs of exclusive-NOR gate 203, with the other input being the output of the gate delayed by one bit period T_B. The one-bit delay can be implemented by a clocked

25   shift-register. The resulting data signal $m_d(t)$ contains the data of m(t) encoded such that a logical 1 is represented by a change of logic state from the previous bit, and a logical 0 is represented by no change in logic state from the previous bit. The data signal $m_d(t)$ is then used by the symbol encoder 205 to vary the impedance of the antenna as described above. The reflected carrier signal is thus modulated with differential phase-shift keying

30   and can be demodulated by the receiver 120 of the external device with the exemplary

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implementation shown in Fig. 5B. There, the correlator 125, made up of mixer 121 and integrator 122, correlates the signal x(t) with the same signal delayed by one symbol period T_S, the delay being implemented by delay element 126. The correlation is performed over the symbol period T_S such that each symbol of the received carrier signal

5   x(t) is correlated with the previous symbol in x(t) which simultaneously demodulates the carrier and differentially decodes the message data signal $m_d(t)$. The output of the correlator is then converted to digital data by symbol decoder 123 to recover the message data signal m(t).

It should be appreciated that the demodulation of the carrier signal by the external

10   device in any of the embodiments described above may be accomplished by either analog circuit elements or entirely in the digital domain. In the latter case, the reflected carrier signal is received by the antenna of the external device and digitized using a sampling rate at least twice that of the carrier frequency. The correlation operations may then be performed by code executed by the microprocessor or a dedicated digital signal

15   processor.

A complicating factor in implementing a passive telemetry system that has not been mentioned thus far is the backscattering of the carrier signal by surfaces other than the antenna of the implantable device. When the carrier signal is transmitted to the implantable device by the external device, the signal is reflected by other surfaces in the

20   environment and received by the external device antenna at various phase angles in addition to the modulated carrier signal. Even if a reference carrier is properly generated or differential phase-shift keying is used, the additive effects of this backscattered radiation decreases the phase distance between the symbols of the modulated carrier. For example, the 0 and 180 degree phase shifts used to represent symbols in binary phase-

25   shift keying may be received by the external device as 0 and 20 degrees of phase shift. In order to compensate for this effect, the voltage thresholds used by the symbol decoder 123 to convert the output of the correlator 125 into digital data need to be adjusted accordingly so that the actual phase shifts detected by the correlator are interpreted as symbols. Such adjustments of the symbol thresholds may be made manually or

30   dynamically using a training sequence.

Although the invention has been described in conjunction with the foregoing specific embodiment, many alternatives, variations, and modifications will be apparent to those of ordinary skill in the art. Such alternatives, variations, and modifications are intended to fall within the scope of the following appended claims.